

LCA Case Studies

Life Cycle Assessment of Chemical Agent Resistant Coatings*

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Abstract

The Department of Defense (DoD) and the U.S. Environmental Protection Agency (EPA) have established a history of cooperation on a wide variety of pollution prevention research efforts, which apply the principles of Life-Cycle Engineering and Design (LCED) to DoD operations. DoD and EPA jointly sponsored this project, with funding from EPA and DoD's Strategic Environmental Research and Development Program (SERDP), to focus on using Life Cycle Assessment (LCA) principles for optimizing the process of painting military vehicles with chemical agent resistant coatings (CARC). The objectives were to identify environmental and energy burdens of the CARC painting life cycle, and to identify and test potential improvements on a life cycle basis.

This LCA of CARC includes difficulties and lessons learned while conducting all three LCA components. The streamlined life-cycle inventory (LCI) involved quantification of environmental and energy burdens associated with the CARC life cycle. Based on the results of the LCI, a preliminary scoping of potential impacts, and a knowledge of alternative CARC painting materials and equipment, five alternatives for the application of CARC were identified. The life-cycle impact assessment (LCIA) of these applications used the equivalency method for impact characterization. The life-cycle improvement assessment (LCImA) results suggested that one application, based on combining an alternative primer and the turbine high-velocity, low-pressure (HVLP) spray painting system, should be subjected to test and evaluation. The LCIA gave this alternative the lowest environmental impact potential scores for seven of nine impact categories compared to the five other alternative systems evaluated. The preferred alternative was technically evaluated in the laboratory against the baseline CARC system using test panels painted at two Army bases. Preliminary results indicate that the preferred alternative performs equal or better than the baseline system at lower cost and with reduced environmental impact potential.

Keywords: CARC, chemical agent resistant coatings, LCA; chemical agent resistant coatings, LCA; department of defense, DoD method, chemical agent resistant coatings, LCA; life-cycle improvement assessment, chemical agent resistant coatings; life-cycle impact assessment, chemical agent resistant coatings

1 Introduction

In 1988, EPA established the Waste Reduction Evaluations At Federal Sites (WREAFS) program to provide technical assistance to Federal departments, agencies and services. During this time, following legislation and Executive Orders, DoD services have passed policies and issued guidance for implementing some level of pollution prevention activity at every facility (DoD, 1996a; 1996b; 1996c). DoD and EPA initiatives have supported pollution prevention research within the Federal community ranging from the management of battery shops to the design of advanced composites (EPA, 1995a).

DoD has institutional experience with life-cycle perspectives as a process of costing out new weapons systems. Life-Cycle Costing (LCC) was developed by DoD during the 1960s and incorporated as policy by DoD Directive 5000.1 in 1971 (HENN and FAVA, 1994). The impetus for LCC had developed along with increasingly complicated and technically advanced weapons systems, which entailed much higher post-acquisition costs in areas such as training, maintenance, technical upgrade, and operation. In this situation, purchasing a system on the basis of lowest bid would not be beneficial if that same system proved to be more costly to deploy and maintain over its life cycle.

Although the conceptual basis for LCA is similar to LCC (both recognize the existence of impacts beyond just those incurred in a manufacturing operation and that the changes in one part of the system can ripple both up and down through the life cycle), the DoD method is to include costs borne by DoD only from the point of acquisition, which in most cases eliminates the first stage(s) of the life cycle. Further, in applying LCA methodology, DoD is motivated to define environmental and energy impacts in cost terms. Thus, we find DoD personnel developing conceptual approaches that are sometimes referred to as "Environmental Life-Cycle Costing" (PERRY, 1994), or "Environmental Accounting". Components of DoD use additional similar terms, such as the Army's "Life-Cycle Environmental Assessment" (which

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is more LCA-oriented) and there does not yet appear to be a common definition or standard approach.

LCED projects, like the one discussed in this article, apply the Society of Environmental Toxicology and Chemistry (SETAC) methods for LCAs to DoD operations to demonstrate the methodology and to develop a compendium of demonstrations and lessons learned that can later be integrated into a guidance document for life-cycle design for the use of DoD commands and acquisition managers.

2 Chemical Agent Resistant Coatings (CARC)

2.1 Purpose and applications of CARC

Due to its responsibilities for national defense and the effective implementation of modern warfare, the DoD has requirements for extremely unique products that have no equal in the private sector. One such product is a paint coating used on vehicles for protection from chemical warfare agents.

Chemical warfare agents are capable of penetrating the matrix of the alkyd paints that were used on military vehicles before CARC became available. Once contaminated, the paint would tend to slowly release the toxins over time, endangering people's lives. Decontaminating such a vehicle would require stripping the entire paint coating away and treating the hazardous waste. By contrast, CARC is an extremely hard coating that resists penetration. This allows a military vehicle to be decontaminated in the field without stripping the paint. Further, because the CARC paint must also camouflage military vehicles, it has to deliver a low visibility finish and minimal heat and radar signatures. CARC is used on a variety of military vehicles and equipment from armored tanks and artillery pieces to unarmored vehicles and equipment. Therefore it has to perform well not only on composite armor, steel and aluminum substrates, but also

on fiberglass and wood. A process flow diagram of stripping CARC from a vehicle and repainting it is provided in Figure 1.

2.2 Composition of topcoat and primer

CARC is formulated with a variety of pigments, heavy metals, and solvents (→ *Table 1*). It cures rapidly after application as a rough, hard, and inflexible coating. Prior to applying the CARC topcoat, the vehicle is cleaned and primed. The most commonly used primer is a Niles two-part epoxy, thinned with alcohols and xylene. *Table 2* provides a breakdown of the chemical constituents of the baseline and alternative primers.

Two Army installations participated in this study, and originally both had used the Bink's Model 7 spraying system, but due to environmental considerations, had changed over to the Mark 1 HVLP guns. While this change led to better transfer efficiency, it also created several problems. CARC is a much heavier, higher solids paint than found in most commercial applications for which the HVLPs had been designed. Some installations found that, in order to be able to force CARC topcoat through an HVLP gun, it had to be thinned by as much as 20% to avoid plugging problems, although one of the sites in the study made limited use of thinner in the topcoat. Installations typically found problems with plugging, transfer efficiency not meeting commercial claims, extended production times to deal with cleaning clogged equipment, and increased use of thinner.

In a report published by the LCED Program (EPA, 1996), an LCA of CARC identifies the environmental impacts of five alternatives entailing the primer, thinner, CARC topcoat, and application equipment. The recommended alternative would change the existing primer and application equipment, but retain the existing thinner and topcoat.

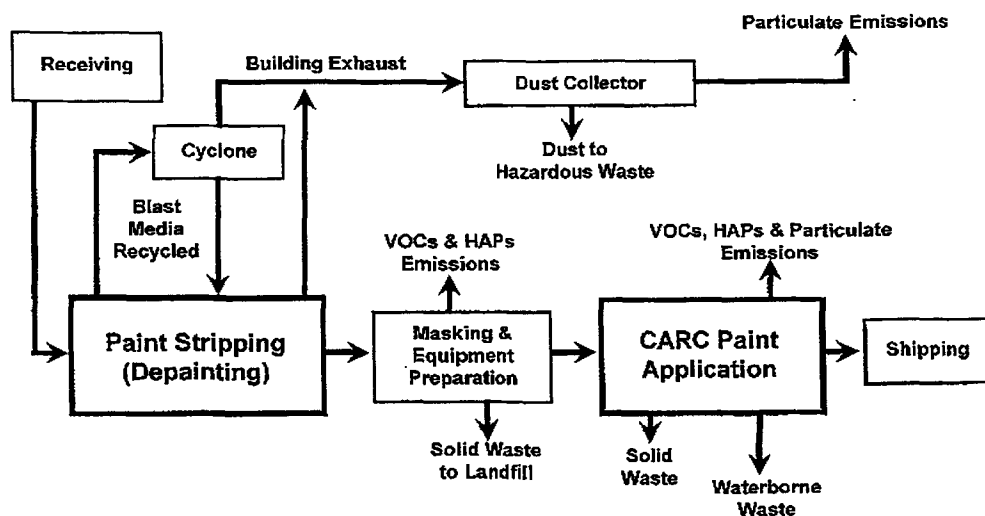


Fig. 1: CARC paint-stripping and painting process flow

Table 1: Percent composition of baseline CARC topcoat

CHEMICAL CONSTITUENTS	MIL-C-53039A (Hentzen 383 Green Zenthane) 08605GUZ-GD (%)
Methyl Isoamyl Ketone	23.8
Magnesium Ferrite Pigment	3.9
Aromatic Hydrocarbons ⁽¹⁾	1.5
Butyl Acetate	1.2
VM&P Naptha	4.8
Xylene	2.0
Cobalt Chromite Green Spinel Pigment	3.9
Trivalent Chrome	6.9
Hexamethylene Diisocyanate	26.0
Diatomaceous Silica Pigment	26.0
TOTAL	100

⁽¹⁾ Mix of C8s to C10^{*}

The typical CARC paint system identified by scoping included the following materials evaluated in the LCI: one-component topcoat (→ Table 1), two-component epoxy primer (→ Table 2), and thinner (A-A-857B). The primer is prepared by mixing four parts of Part A with one part of Part B. Even though a different thinner (MIL-T-81772) was used by most of the other bases surveyed, the thinner (A-A-857B) is used by Fort Eustis because they claim it works better in hot and humid weather.

Aluminum oxide media with high pressure air blasting was selected as the depainting technique. Aluminum oxide is preferred by the Army over other blasting media for the depainting process, because of its high efficiency and low cost. The painting technique selected for the LCI was HVLP spray painting.

Table 2: Percent composition of baseline and alternative CARC primers

CHEMICAL CONSTITUENTS	BASELINE (Niles, 2-part epoxy, solvent thinned)		ALTERNATIVE (Deft, 2-part epoxy, water thinned)	
	53022A 4 part (%)	53022B 1 part (%)	53030A 4 part (%)	53030B 1 part (%)
Epoxy resin solids	22	23	16.03	71.17
Proprietary ingredients		2	0.10	0.06
TiO ₂	20		33.96	
Extenders (Pigment) ⁽¹⁾	18		27.85	
Xylene		11		
n-Butyl Acetate	26			
MIBK	2	28		
Zinc Phosphate	4			
Diethylenetriamine		8		
2-Ethoxyethanol		11		
n-Butyl Alcohol	8	17	10.83	
Aromatic hydrocarbons			11.26	4.13
Nitroethane				24.64
TOTAL	100	100	100	100

⁽¹⁾ MSDS reports 38% proprietary ingredients, which were assumed to be divided between TiO₂ and pigment extenders, respectively, as 20% and 18%

3 CARC Inventory

A streamlined LCI was conducted by Pacific Environmental Services (PES) for a baseline CARC paint system, which included a typical topcoat, thinner, and primer combination determined from a telephone survey of 13 major U.S. Army installations (HENDRICKS et al., 1995). The scoping survey and input from EPA personnel were used to identify a typical CARC paint system, which was based primarily on the products and techniques used at the U.S. Army's Transportation Center at Fort Eustis, Virginia.

3.1 Method

The LCI involved collection of secondary environmental and utility data that describe the production of components for the CARC painting/depainting system, their raw materials, paint application and depainting, and disposal of spent CARC and blast media. These data include the raw materials used, water and energy requirements, atmospheric emissions, liquid wastes, and solid waste streams. The summation of these data constitutes the baseline LCI of CARC usage at Fort Eustis. This baseline included most of the inputs and

outputs from every operation used, from processing the basic raw materials, through all operations involved in taking the material from the earth to the final product use, final product removal, and disposal of the residue material back to the earth. Where primary process information was missing, streamlining measures were taken, and engineering estimates and assumptions were made. With this approach, it was possible to develop an "order-of-magnitude" estimate for the CARC LCI. The LCI study was further limited in scope by focusing on evaluating the main reactions and excluded the low concentration ingredients (less than 1 percent) and catalysts used in the process reactions. All co-product allocation procedures were based on mass.

The functional unit (FU) used was 1,000 ft² of painted surface, because the important requirement for any type of paint is the amount of materials required to produce a good finish over a specific area.

Several of the chemical components in the streamlined CARC life cycle described in the draft LCI by PES (HENDRICKS et al., 1995) were revised by Battelle to fill in data gaps or to provide more recent data, as part of the scoping effort for the LCIA discussed below. Additional LCI data were provided for manufacturing the following chemicals: adiponitrile, cobalt chromite green, hexamethylenediamine, magnesium ferrite, phosgene, sodium cyanide, and sodium dichromate.

Emissions for electrical production, crude oil refining, and natural gas production were taken from Battelle's own LCI databases. The electrical production model calculates the pollutant loadings for the national electrical grid based on the fractions of power created from coal, hydrocarbons, nuclear, hydropower, wind, etc. The crude oil and natural gas models included detailed data on many of the primary refinery chemicals such as hydrogen, propane, aromatic 100, etc.

Emissions data were also determined by obtaining production quantities for manufacturers of the chemicals of interest in SRI International's (1993) 1993 Directory of Chemical Producers and cross referencing the manufacturer with 1993 Toxic Release Inventory (TRI) emission data. 1993 was the latest year for which both SRI and TRI data were both available. Production tables were available in the SRI directory for several chemicals of interest to the CARC study, thus allowing direct calculation of the emission rates per pound of product production. However, chemical producers listed in the SRI directory often produced several chemicals. Specific plants were selected for their production of the chemical of interest alone or with a small number of related products, thus minimizing the need for extensive allocation of the individual TRI facility emissions. Phosgene and sodium cyanide emissions data were taken directly from the SRI/TRI data.

Emission data were collected in the form of individual constituents whenever possible. In many cases emissions data

were available for individual chemicals and in other cases the only readily available data were for subcategories of emissions (e.g., VOCs or aromatic hydrocarbons). Although the individual chemical data were used to conduct the LCIA described below, they were aggregated into subcategories for simplifying presentation of the LCI results (→ Table 3).

Table 3: Aggregated baseline CARC LCI data summary ⁽¹⁾

LCI Components ²	Units	Quantity
ENERGY CONSUMPTION		
Natural Gas	J/FU	1.51E+10
Electricity	J/FU	8.74E+08
Steam	J/FU	6.18E+08
RESOURCE USE		
Water	kg/FU	1.98E+04
Crude Oil	kg/FU	1.25E+03
Intermediate Materials	kg/FU	4.82E+01
Bauxite	kg/FU	3.81E+01
Sodium Chloride	kg/FU	1.95E+01
Other Geologic Sources	kg/FU	1.87E+01
AIR EMISSIONS		
CO ₂	kg/FU	1.36E+02
SO _x	kg/FU	9.79E+00
VOCs (Chemicals not Specified)	kg/FU	6.81E+00
NO _x	kg/FU	2.77E+00
PM (Size not Specified)	kg/FU	2.72E+00
Mix of Aliphatic & Aromatic Compounds	kg/FU	1.54E+00
Aliphatic Compounds	kg/FU	9.26E-01
CO	kg/FU	6.29E-01
Aromatic Compounds	kg/FU	2.99E-01
PM ₁₀	kg/FU	1.41E-01
Inorganic Compounds	kg/FU	1.33E-02
Lead	kg/FU	3.97E-04
WATER EMISSIONS		
Wastewater	kg/FU	1.63E+03
Mobile Ions (Unspecified)	kg/FU	1.58E+01
Cations	kg/FU	6.61E+00
Anions	kg/FU	5.18E+00
Oil & Grease	kg/FU	1.61E-01
Aromatic Hydrocarbons	kg/FU	3.23E-04
Dissolved Solids	kg/FU	3.09E-07
COD	kg/FU	2.05E-09
Suspended Solids	kg/FU	1.06E-09
BOD	kg/FU	6.20E-10
SOLID WASTES		
Hazardous Wastes	kg/FU	3.67E+01
Solid Wastes	kg/FU	2.82E+01
Radioactive Wastes	kg/FU	2.50E-09
Other Combustion Wastes	kg/FU	1.63E-09

⁽¹⁾ Inventory items are listed in descending order of quantity within subcategories

⁽²⁾ Constituents in small quantities were aggregated for this summary

Examples of individual constituents within subcategories are:

Other Geologic Sources (Iron Ore & Coal):

Aliphatic Compounds in Air Emissions (Acetone, Ethylene & Hexane):

Cations in Water Emissions (Aluminum, Copper & Zinc).

3.2 Transparency and data gaps

Several of the chemicals did not have production data to allow for proper emissions allocation on a per pound basis (e.g., sodium dichromate) and some of the organic chemi-

cals were made in plants producing such a tremendous variety of chemicals that allocation would require an extensive understanding of the specific facility (e.g., methyl isoamyl ketone produced by Tennessee Eastman). In addition, no emissions data were obtained for the production of isopropyl alcohol and butylcellosolve. Thus, the LCI data exclude emissions from manufacturing of these four chemicals. Further, data obtained for the manufacturing of two pigments, cobalt chromite green and magnesium ferrite, did not fit into the model. Emissions associated with manufacturing these pigments were listed, but not quantified, in the available references. Finally, in order to obtain more readily separable data, information on hydrogen production was based on the caustic soda production process, rather than the more common hydrocarbon derivation.

3.3 Inventory results

An aggregated summary of resources used and emissions released in kg/FU from all life-cycle stages is provided in Table 3. The inventory items in this summary are listed in descending quantity within each major category. The primary source of energy consumption is natural gas followed by electricity. Water and crude oil are the two resources used in greatest quantity. The two air emissions released in the greatest quantity are CO_2 and SO_x . Total VOCs increases to 7.7 kg/FU after adding individual volatile organic chemicals aggregated in other subcategories. Wastewater is the greatest liquid emission, which includes mobile ions as the highest subcategory of water pollutants. The greatest quantity of solid wastes is hazardous wastes.

Of the total LCI emissions and wastes, the depainting and painting operations contributed greater than 80 percent of each of the following emissions: methyl isoamyl ketone, xylene, aromatic hydrocarbons, and hazardous solid wastes. The hazardous solid wastes (36.7 kg/FU) included spent CARC and primer and discarded aluminum oxide from the depainting operations.

Essentially all of the criteria air pollutant emissions (CO_2 , CO , TSP, PM_{10} , SO_x , Lead, NO_x), including the majority (88%) of the VOCs, were released during the intermediate material manufacturing stage of the CARC life cycle. Essentially all of the water emissions and all solid wastes, except hazardous waste, were also released during the intermediate material manufacturing stage.

4 CARC Impact Assessment

An LCIA (as defined by SETAC, 1993) involves the examination of potential and actual environmental and human health effects related to the use of resources (energy and materials) and environmental releases. An LCIA is divided into the following three phases: Classification, Characterization, and Valuation. The characterization phase typically

includes normalization, which compares the contributed potential impact of the system under investigation to the overall environmental problem magnitude, in order to place the system-level results in perspective relative to the global, regional, or local perspective of the impact. In this study, however, the equalizing value used was the impact quantity for the stressor creating the greatest impact potential for a given impact category.

Classification was conducted after scoping and is the process of linking or assigning data from the LCI by PES (HENDRICKS et al., 1995) to individual stressor categories within the three major stressor categories of human health, ecological health, and resource depletion. This process included creation of complex stressor/impact chains, because a single pollutant can have multiple impacts, and a primary impact can result in secondary (or greater) impacts as one impact results in another along the cascading impact chain. Stressor/impact chains were developed by considering the energy, water, and raw material inputs to each life-cycle stage, as well as the air, water and solid waste emission outputs from each life-cycle stage, and comparing them against lists of potential impacts (e.g., SETAC, 1993; HEIJUNGS, 1992).

Based on the stressor/impact chains developed during classification, the following nine impact categories were selected for impact characterization: photochemical oxidant creation (smog formation), ozone depletion, acidification (acid rain/fog), global warming (greenhouse effect), human health inhalation toxicity (acute inhalation toxicity), terrestrial toxicity (acute oral wildlife toxicity), aquatic toxicity (acute fish toxicity), land use (for solid waste disposal), and natural resource depletion (including fossil fuels and minerals).

4.1 SETAC Level 2/3 impact description

Characterization involved the analysis and estimation of the magnitude of impacts for each of the stressor categories by using the SETAC (1993) Level 2/3 approach of multiplying equivalency factors times the quantity of a resource or pollutant associated with an FU of CARC. For the Level 2 evaluation, a limited subset of the chemicals identified during the LCI had already been assigned impact equivalency units in published documents. Examples of groups of chemicals that have been evaluated for impact equivalency include nutrients, global warming gases, ozone depletion gases, acidification potential chemicals, and photochemical oxidant precursors (HEIJUNGS, 1992; Nordic Council, 1992).

New impact equivalency units were created for some chemicals identified in the baseline or alternative LCIs, by a modification of the Level 3 Toxicity, Persistence, and Bioaccumulation Potential Approach, by adapting the hazard ranking approach described in an EPA (1994) report, which was summarized and published by SWANSON et al. (1997). This included evaluation of impacts (e.g., toxicity to humans, fish, or wildlife) other than the impacts evaluated in Level 2, al-

though a few chemicals with multiple impacts were evaluated by both the Level 2 and 3 approaches. Some data were obtained from the EPA (1994) report, which described a method for ranking and scoring chemicals by potential human health and environmental impacts. Toxicity or persistence data for chemicals not included in the EPA (1994) chemical ranking report were obtained from electronic, non-bibliographic databases available through the MEDLARS or CIS database clearinghouses.

Evaluation of the magnitude of resource depletion impacts associated with the life cycle of CARC started with the resource use inventory information from the LCI by PES (HENDRICKS et al., 1995). Resources included in the analysis involved both flow resources, such as water, and stock resources, such as minerals, primary energy sources (e.g., gas, oil, and coal), and land. These impacts were evaluated from a sustainability (time-metric standpoint), which considers the time to exhaustion of the resource. Information on the world reserve base and production of minerals came from various U.S. Bureau of Mines (now called the U.S. Geological Survey, Minerals Information Center) publications. Information for energy sources came from the Energy Information Administration, U.S. Department of Energy.

4.2 Use of the AHP

Valuation involved assigning relative values or weights to different impacts, so they can be integrated across impact categories for use by decision-makers. The same approach was used for economic and performance measures, so that a total score for all decision criteria could be determined. The valuation method used in this study is known as the Analytical Hierarchy Process (AHP). AHP is a methodology for supporting decisions based on relative preferences (importance) of pertinent factors (SAATY, 1990). Preferences were expressed pairwise in a structured manner supported by a software package known as Expert Choice™.

The AHP process involves a structured description of the hierarchical relationships among the problem elements, beginning with an overall goal statement and developing a decision tree, where the branches of the tree include major and minor decision criteria. Assignment of weights was done as a group exercise, where a four member team was asked to reach a consensus on the weight factors prior to their being entered into the model. The advantages of the AHP method include its structured nature and the fact that the valuation process does not deal with the entire set of criteria at one time, an effort that would be overwhelming. Rather, the team expresses preferences in a pair-wise manner supported by EC.

One of the key assumptions in applying the AHP method is that the environmental, cost, and performance perspectives of the team members determining weight factors are assumed to be a reasonably good cross section of the views held by

similar stakeholders in the decision process. Because the team included one cost engineer, one paints/coatings specialist, a civil engineer, and an ecologist, the valuation team mix, and the resulting weights, were considered reasonable.

4.3 Impact assessment findings

The environmental impact significance of the resource and emission data from the baseline CARC LCI was characterized (quantified) using the equivalency factor (Level 2/3) approach. The importance of each individual resource or chemical within an impact category was determined by multiplying the equivalency factor times the inventory value in lb/FU. The results of these calculations for each resource or emission are considered "factored scores" within each of the nine impact categories. The factored scores are then normalized by dividing by the largest "factored score" within an impact category. Environmental impact valuation involves summing the normalized, "factored scores" by impact category and multiplying the sum by the weighting factor for the appropriate impact category.

The impact valuation scores for the baseline CARC system indicated that the impact categories of greatest concern (highest impact scores) are ozone depletion potential (0.362), acid deposition (0.226), and human inhalation toxicity (0.213). The ozone depletion potential impact score is primarily due to the carbon tetrachloride air emissions associated with manufacturing Part B of the primer. The acid deposition impact score is primarily due to the SO_x air emissions associated with manufacturing Parts A & B of the primer. The human inhalation toxicity impact potential score is primarily due to the chlorine air emissions associated about equally with manufacturing Parts A & B of the primer and the CARC topcoat. All three of the toxicity impact categories had a combined impact valuation score of 0.314, which makes the combined impact scores for toxicity second only to ozone depletion potential in terms of relative concern for environmental impacts.

Table 4 provides the life cycle impact valuation calculations for one of the alternatives identified under the study, which, due to the low score, was selected for technical evaluation on-site. In addition to the environmental impacts, economic and performance impacts were calculated and integrated under the final score.

5 Improvement Assessment

5.1 Best alternative

On the basis of the LCA, it was determined that the alternative with the best potential for reductions in most impact categories was a substitution of a water-thinnable primer and use of turbine-powered HVLP spray equipment. This option showed greater reductions in energy and resources

Table 4: Life cycle impact valuation calculations for alternative primer and equipment

Categories	AHP Weighting Factor	Normalized Factored Score	Weighted Score	Score by Scale
GLOBAL				
OZONE DEPLETION	0.17983	0.265	0.048	
GLOBAL WARMING	0.11328	0.677	0.077	
FOSSIL FUELS	0.02855	0.827	0.024	
TOTAL GLOBAL				0.148
REGIONAL				
ACID RAIN	0.06253	1.098	0.069	
SMOG	0.13007	0.721	0.094	
WATER USE	0.01002		0.000	
TOTAL REGIONAL				0.162
LOCAL				
TOXICITY				
Human	0.06155	1.172	0.072	
Terrestrial	0.02052	1.906	0.039	
Aquatic	0.02052	2.554	0.052	
LANDUSE	0.02507	1.497	0.038	
TOTAL LOCAL				0.201
COST				
OPERATIONS & MAINTENANCE	0.08027	1.009	0.081	
CAPITAL	0.03274	1.064	0.035	
TOTAL COST				0.116
PERFORMANCE				
APPLICATION EQUIPMENT				
Transfer Efficiency	0.01713	1.000	0.017	
Surface Quality	0.03522	2.000	0.070	
PRIMER				
Temperature/Humidity	0.05841	0.833	0.049	
Cure Rate	0.02013	1.000	0.020	
Surface Preparation	0.02072	1.000	0.021	
Cleanup	0.02057	1.500	0.031	
THINNER				
Thinning Ratio	0.03144	1.000	0.031	
Surface Quality	0.03144	1.000	0.031	
TOTAL PERFORMANCE				0.271
TOTAL SCORE				0.898

than the other alternatives, wherein primers and spray equipment were considered separately.

Like the current solvent-based primer, the alternative primer is an epoxy-polyamide system but it does not require a solvent for cleanup. Neither system requires thinning for application, but unfortunately the levels of solvent required for cleanup were not tracked closely, requiring some engineering judgement to estimate solvent reduction potential of the alternative. Since the alternative meets military specifications it is expected to perform acceptably for adhesion and corrosion resistance.

The alternative spray equipment is the Can-am turbine HVLP, which uses turbine technology instead of the traditional method of passing compressed air through a conversion zone in order to convert high pressure, low volume air into HVLP. This technology decreases system turbulence which in turn reduces overspray significantly.

5.2 Economic Assessment

The annualized costs estimated in this analysis were restricted to internal costs (i.e., costs associated with the Army's depainting and painting operations). These costs were further classified into direct and indirect costs. Direct costs are closely associated with the depainting and painting operations and include expenses related to capital expenditures for building, equipment, renovations, etc., and operating cost such as operating labor, materials, utilities, maintenance, and waste disposal. Indirect costs are costs which are incurred, but might be spread across several facilities on base, and included in labor overhead (e.g., compliance, waste storage, insurance, penalties and fines, personal injury and property damage liability).

External costs, such as the land use cost to society of the landfill where the waste is disposed (i.e., alternative uses are precluded), were not included in the analysis. The advantage

of this approach is that information on direct and indirect internal costs was readily available from the Army, suppliers, and private industry. Restricting the scope in this manner permitted more focus on data analysis.

The factored estimate costing procedure (PETERS and TIMMERHAUS, 1991) provides a straightforward approach to preparing cost estimates with a medium level of accuracy. Capital costs are accurate within $\pm 40\%$, and operating costs within $\pm 03\%$. Getting a more accurate estimate requires development of a detailed design, complete equipment specification, acquisition of vendor quotes, etc.

The annualized cost to repaint and paint Army vehicles was estimated using a factored estimate approach. A base case and five alternative cases were evaluated. Fort Eustis was selected as the baseline site, so its plant capacity; staffing; and paint-, primer-, thinner-, and abrasive media-usage rates were used to estimate typical costs. The alternative selected for evaluation posted annual cost savings of more than \$ 230,000.

5.3 Process inconsistencies between sites

Late in the study, a discovery was made that has significant bearing on implementing future changes: despite technical orders and standing operating procedures, CARC painting systems are not consistently applied. As mentioned earlier, Army installations would either thin or use CARC directly on the basis of judgement and experience. We also found that some installations would bypass the priming system entirely, using the CARC topcoat as a kind of "unicat" material. This eliminates emissions associated with priming, but it is not known what long term impacts may be created (e.g., changes in the endurance of the topcoat and the frequency of the painting cycles). Further, as noted earlier, one of the sites used thinner A-A-857B because of its better performance under heat and humidity, while other Army sites did not use the product because it was not indicated for CARC systems. For the sake of consistency, it had to be assumed that all sites would follow proper procedures, but for the designer, awareness that such is not always the case is necessary.

6 Technical Evaluation

6.1 Description of evaluation parameters

The evaluation consisted of parameters for application equipment, primers and thinners, which were the three CARC system components that were varied in the five alternatives compared to the baseline. Surface quality and transfer efficiency (the ability of the application equipment to minimize overspray and bounceback) were selected as the two evaluation parameters for application equipment. The ability of the application equipment to provide sufficient atomization

and desired thickness levels and coverage areas were not chosen as evaluation parameters, due to information from equipment manufacturers stating that these issues could be ignored assuming the proper selection of nozzles and tips. The ability of the application equipment to effectively apply CARC was ranked according to the surface quality of the applied coating. An acceptable finish is one with no visible application induced surface blemishes (e.g., orange peel, blistering).

The major issues of primers are corrosion inhibition, adhesion, and cure rate. Since the primers under evaluation in this study are all MILSPEC, they are assumed to provide sufficient corrosion inhibition. Adhesion was evaluated in terms of the level of cleaning of the substrate (surface pretreatment) required for acceptable adhesion and with respect to impacts resulting from changes in environmental conditions, such as temperature and humidity. Cure rate and ease of cleanup of the primer were evaluated with respect to the impact on the painting schedule and the level of effort required.

The thinner evaluation parameters included thinning ratio (thinning effectiveness) and film characteristics. Thinners were evaluated based on the percentage of thinner needed to dilute CARC to within sprayable viscosity limits. Thinners were also ranked according to the ability of the thinner to provide an acceptable finish. Thinners that evaporate too slowly or too quickly can cause undesirable surface defects such as sagging or running and blushing, popping, and orange peel.

6.2 Evaluation

In order to get a sense of how the alternative might perform at different sites, two sites were selected to participate in the technical evaluation of the primer and spray equipment: Fort Eustis, Virginia and Fort Campbell, Kentucky. Fort Eustis exhibits higher humidity and temperature and the vehicles it paints are often forward deployed in salt-laden environments. Fort Campbell is located in the Midwest and most of its vehicles do not get deployed to such hostile environments.

Steel and aluminium coupons were used to test the alternative primer and spray equipment (however, at the conclusion of the test, each site asked to paint a full sized vehicle: a Humvee at Fort Campbell and a forklift at Fort Eustis). During the test, it was noted that certain vehicles have fiberglass hoods and there is a significant amount of wood that is painted with CARC. Unfortunately, this was discovered too late to include these substrates in the test.

One area of concern was the use of a water-based primer in a high humidity environment. During the test, Fort Eustis did encounter repeated difficulties with the primer running on the test coupons, however, the personnel indicated that they felt the problem could be controlled if they had more time to work with the product and develop an understanding of its characteristics. Fort Campbell did not encounter problems with the primer.

The turbine HVLP system performed extremely well at both sites. For the test, it was decided that the thick CARC topcoat would not be thinned, and the turbine HVLP was able to apply the paint without clogging. Personnel at both sites commented on the simplicity of design and ease of cleanup, resulting in both timesavings and significant reductions in solvent use. The turbine HVLP achieved a high level of transfer efficiency, requiring about 60% as much paint to cover a full-sized vehicle.

7 Conclusion

The LCA found that alternative number 3, a combination of an alternative primer, thinner and topcoat resulted in the lowest impact across the greatest number of impact categories, although it did not have the lowest impact for aquatic toxicity. This alternative also exhibited potential cost savings of \$ 230,000 per year for each facility working at the Ft. Eustis level of painting operations. The technical evaluation of this alternative supported these findings and demonstrated that cross-media impact of higher solvent usage by the HVLP guns over their predecessors would be eliminated by the new turbine-based HVLP systems. Further, the turbine HVLP dramatically improved transfer efficiencies, resulting in a 40% reduction in product use. Finally, the new system was well received by the painters, who saw several benefits in terms of ease of cleanup and operations in the new systems.

From this study, it appears that LCA principles can be used in a practical fashion to select optimal techniques in painting operations, although the study needs to be completed with a full-scale test and evaluation to confirm the best alternative. The EPA has published guidance on conducting both LCIs (EPA, 1993) and using life-cycle principles in design (EPA, 1995b). The documents are available free of charge from the National Risk Management Laboratory.

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